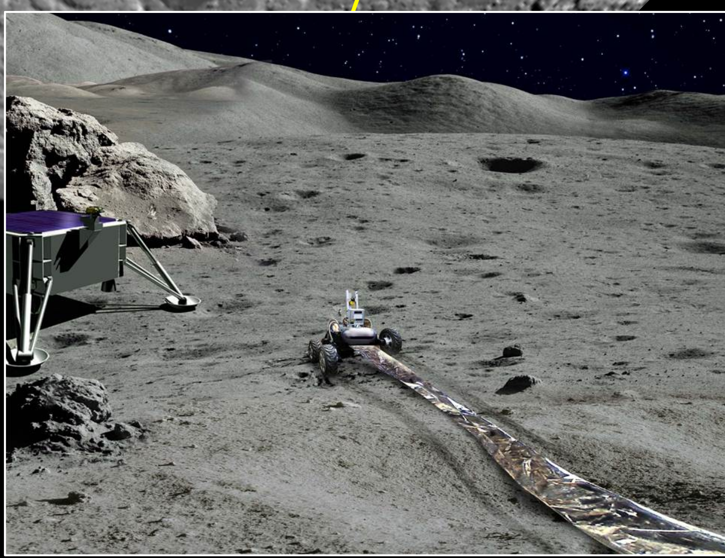
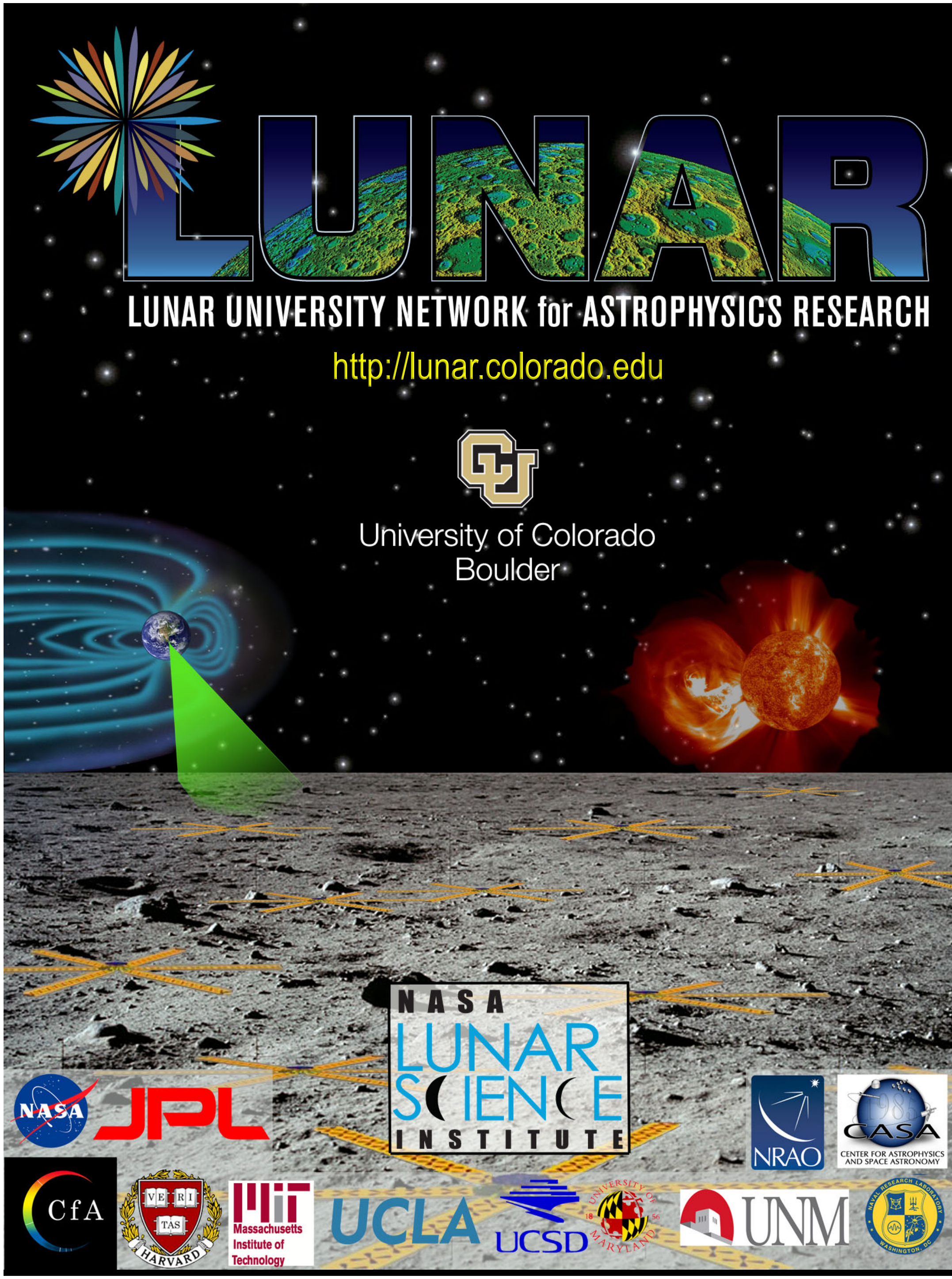
Teleoperation of Rovers on Planetary Surfaces

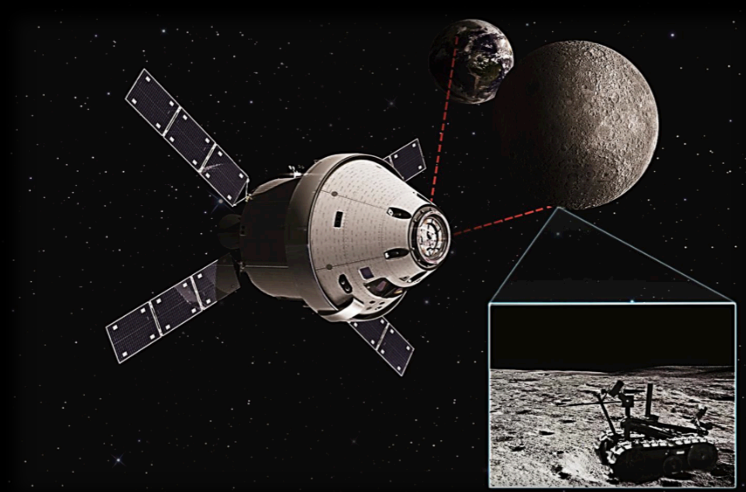


Jack Burns
University of Colorado Boulder
& Lunar University Network for Astrophysics Research



COLLABORATORS

- T. Fong, M. Bualat, NASA Ames
- D. Kring, Lunar & Planetary Institute
- L. Kruger, J. Parker, U. Colorado
- J. Lazio, JPL/Caltech
- J. Hopkins, W. Pratt, S. Norris, Lockheed Martin

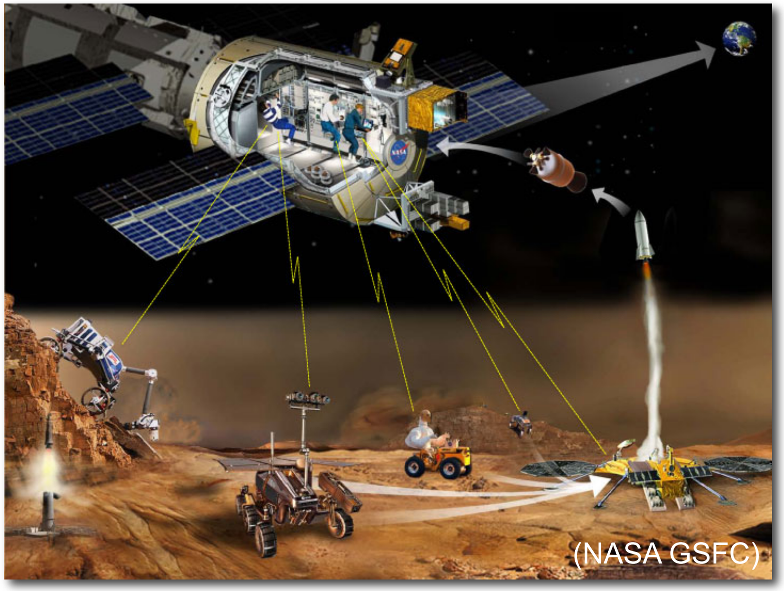


Motivation

Future exploration architecture study teams have made assumptions about how crew can remotely perform work on a planetary surface …

Candidate Exploration Missions

- **Lunar Farside**. Orion MPCV orbital mission (libration point or distant retrograde)
- **Near-Earth Asteroid**. NEA dynamics and distance make it impossible to manually control robot from Earth
- **Mars Orbit**. Crew must operate surface robot from orbit when circumstances (contingency, etc.) preclude Earth control


(NASA GSFC)

Assumptions

- Maturity of crew-controlled telerobotics
- Existing technology gaps (and how these can be bridged)
- Operational risks (proficiency, performance, failure modes)

In 2013, we began testing these assumptions using the ISS. We propose to extend this work to better prepare NASA for future human missions …

From Global Exploration Roadmap (2013)

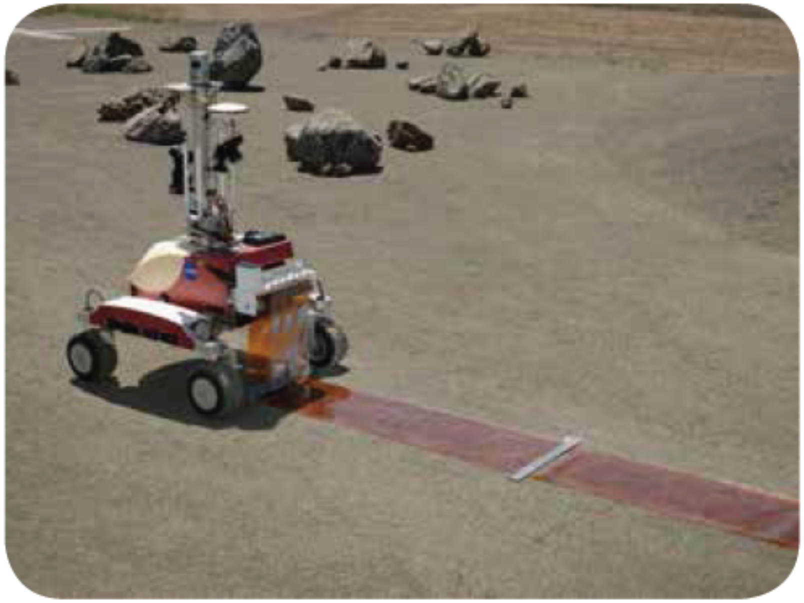
Human-Robotic Partnership

The conceptual architecture represented in the ISECG Mission Scenario provides the opportunity to study ideas which further expand the human-robotic partnership. New mission concepts, defined below, merit further study.

Tele-Presence

Tele-presence can be defined as tele-operation of a robotic asset on a planetary surface by a person who is relatively close to the planetary surface, perhaps orbiting in a spacecraft or positioned at a suitable Lagrange point. Tele-presence is a capability which could significantly enhance the ability of humans and robots to explore together, where the specific exploration tasks would benefit from this capability. These tasks could be characterized by:

- High-speed mobility
- Short mission durations
- Focused or dexterous tasks with short-time decision-making
- Reduced autonomy or redundancy on the surface asset
- Contingency modes/failure analysis through crew interaction



From the ISS, astronaut Chris Cassidy operated this high-fidelity planetary rover, located at Ames Research Center's analogue facility. The ISS is conducting demonstrations such as this to gather engineering data useful to advancing the concept of tele-presence.

Observation:

➔ New mission concepts, such as human-assisted sample return and tele-presence should be further explored, increasing understanding of the important role of humans in space for achieving common goals.

Surface Telerobotics Roadmap

Ground Analogs

Develop telerobotic systems (autonomy, data comm, interfaces)

Implement and test multiple conops

Simulate future human mission concepts

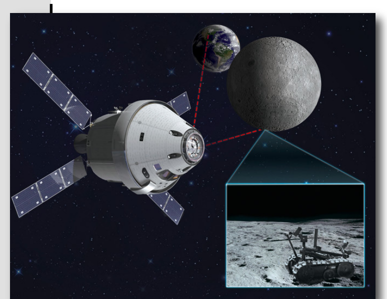
ISS Laboratory

Obtain baseline engineering and operations data

Validate prior ground simulations via high-fidelity ops sims

Reduce risk for future exploration systems (test assumptions)

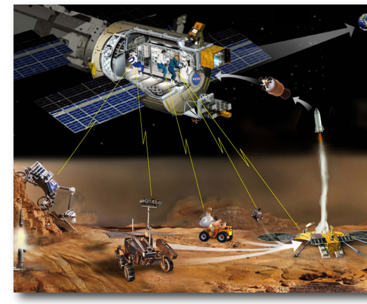
Lunar Orbit



Enable “off-board” autonomy (use flight vehicle computing as part of robot system)

Use cis-lunar environment to prepare for human Mars missions.

Mars Orbit



Enable crew to explore surface using robot as an “avatar”

Enable “off-board” autonomy and data storage (use flight vehicle computing as part of robot system)

TRL 5 **Surface Telerobotics** *TRL 7*

Phase 1 Overview

Key Points

- Demo **crew-control** surface telerobotics (planetary rover) from ISS
- Test **human-robot conops** for future exploration mission
- Obtain **baseline engineering data** (robot, crew, data comm, task, etc)

Implementation

- Lunar libration mission simulation
- Astronaut on ISS (in USOS)
- K10 rover in NASA Ames Roverscape

ISS Testing (Expedition 36)

June 17, 2013 – **C. Cassidy**, survey

July 26, 2013 – **L. Parmitano**, deploy

Aug 20, 2013 – **K. Nyberg**, inspect

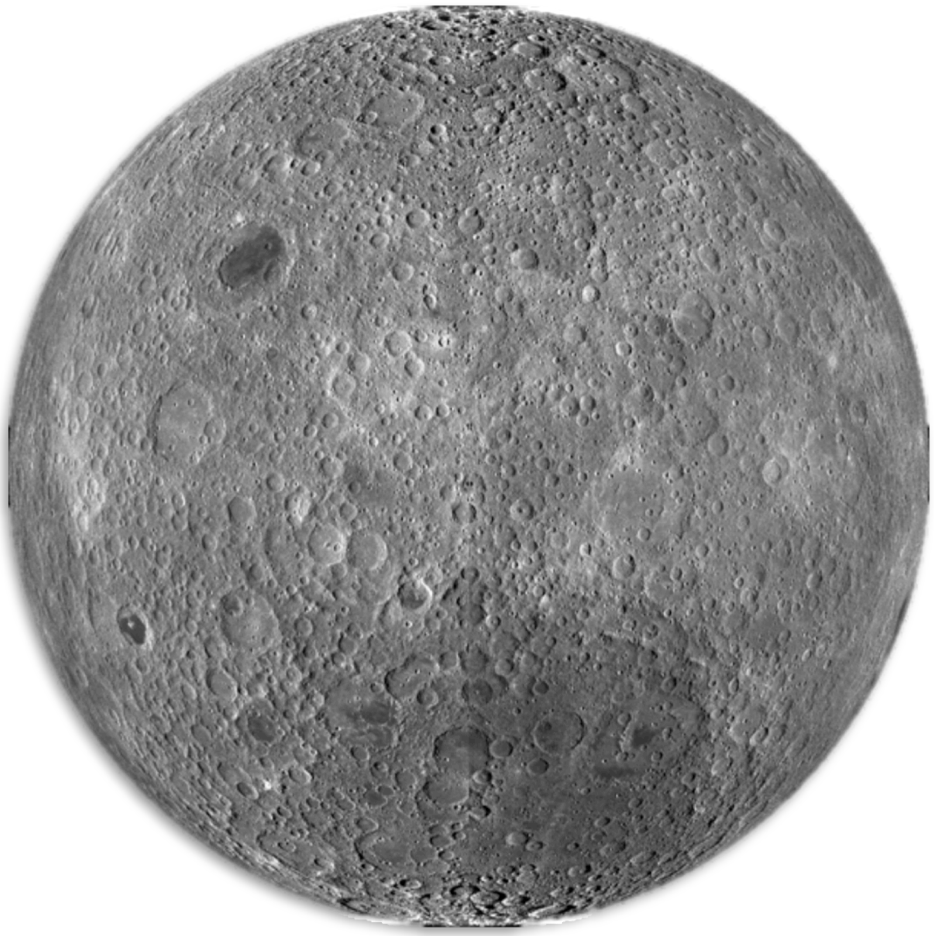
SURVEY

DEPLOY

INSPECT

- **Human-robot mission sim**: site survey, telescope deployment, and inspection
- **Telescope proxy**: Kapton polyimide film roll (no antenna traces, electronics, or receiver)
- **3.5 hr per crew session** (“just in time” training, system checkout, ops, & debrief)
- **Robot ops**: manual control (discrete commands) and supervisory control (task sequence)

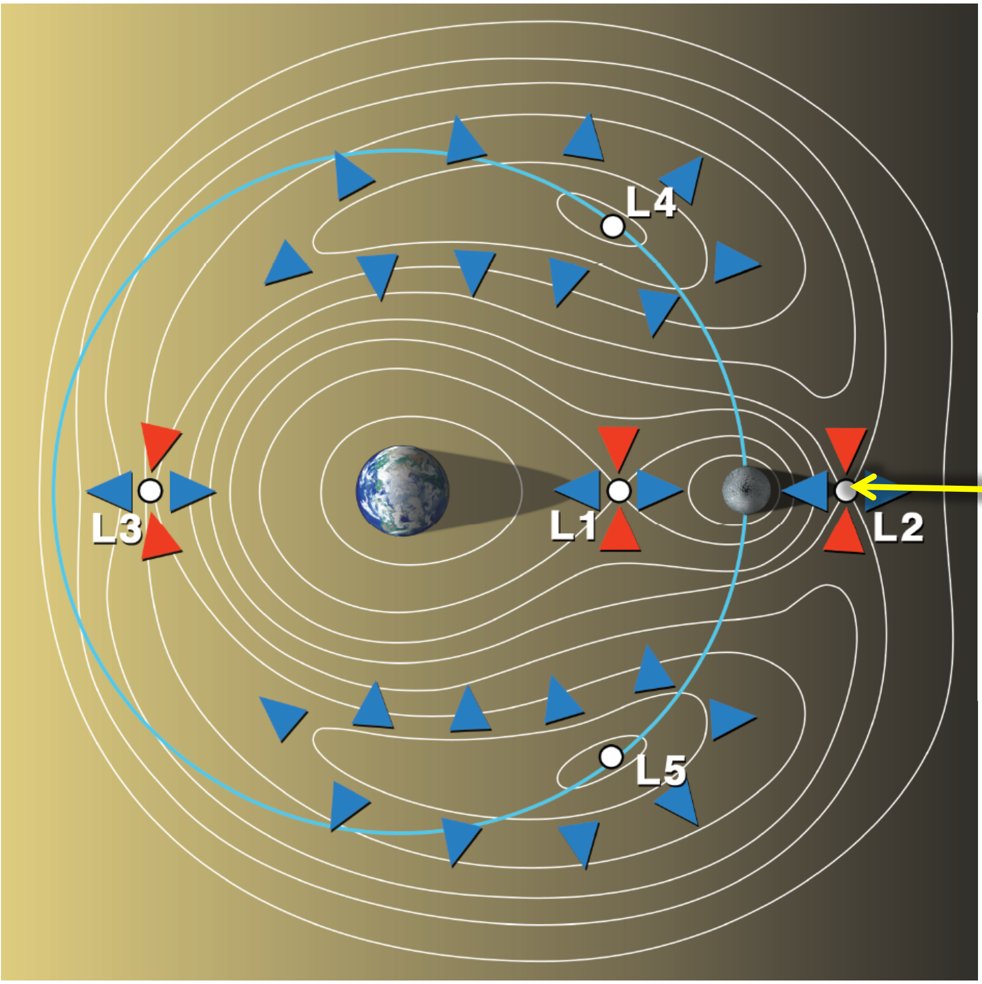
The Lunar Farside

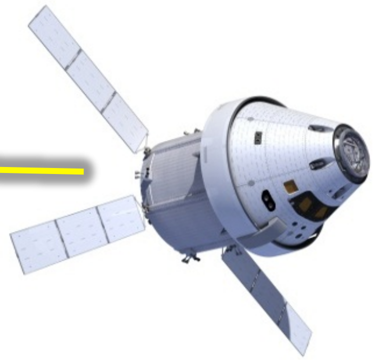


- A whole new, *unexplored* world in Earth's backyard!
- Opportunity to demonstrate human-robotic exploration strategies needed to explore surfaces of the Moon, asteroids, & Mars.
- Lunar farside is dramatically different from regions investigated by Apollo – e.g., 1% maria on farside vs. 31% on nearside.
- Farside includes the South Pole-Aitken basin – possibly the largest, deepest, & oldest impact basin in the inner solar system.
- Because of Earth-Moon tidal locking, farside always faces away from Earth and is, therefore, the only pristine radio-quiet site to pursue observations of the early Universe's *Cosmic Dawn*.

Orion Crew Vehicle at Earth-Moon L2 (or Distant Retrograde Orbit) can teleoperate rover on Farside

- E-M L2 is 60,000 km above farside. Minimal station-keeping to orbit about L2.
- This mission is much less expensive than Apollo-style missions since no lunar lander is required.
- Mission is affordable with NASA's current & notional outyear budgets.
- Timetable for first crewed mission(s) is early 2020's.





Waypoint Mission Concept

Burns *et al.* 2013, ***Advances in Space Research***, 52, 306.
J. Burns, D. Kring, J. Hopkins, S. Norris, J. Lazio, J. Kasper

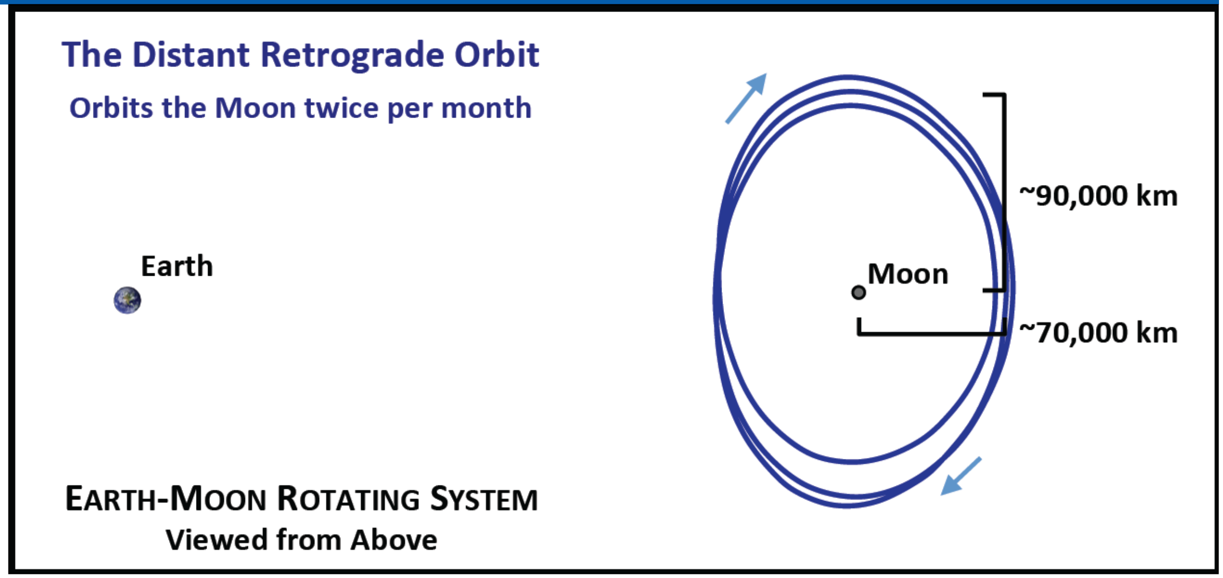
Surface Telerobotics

LUNAR
LUNAR UNIVERSITY NETWORK for ASTROPHYSICS RESEARCH

Distant Retrograde Orbit (DRO)

Jeff Parker & Jack Burns, U. Colorado

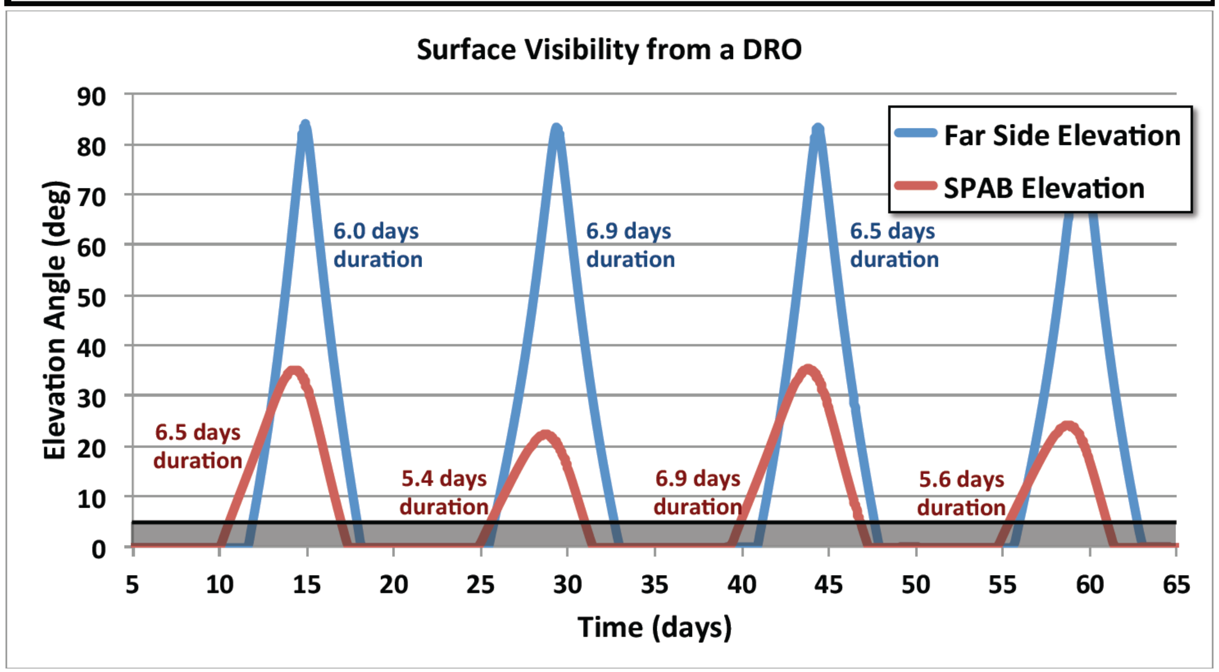
DRO is a very large, stable orbit about the Moon. A space-craft in a DRO orbits the Moon very slowly in a clockwise fashion. The orbit pictured below takes two weeks to traverse; the spacecraft orbits 70,000 – 90,000 km away from the Moon.



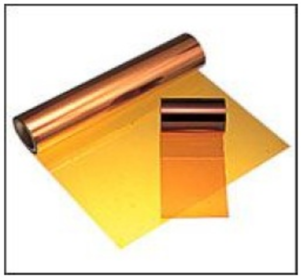
Far-Side Visibility: This orbit spends 12 – 13 days in view of the far side of the Moon each month, in two continuous blocks of time.

Far-Side: A spacecraft is in view of (180°E, 0°S) for 6 – 7 days at a time, with a 5° elevation mask.

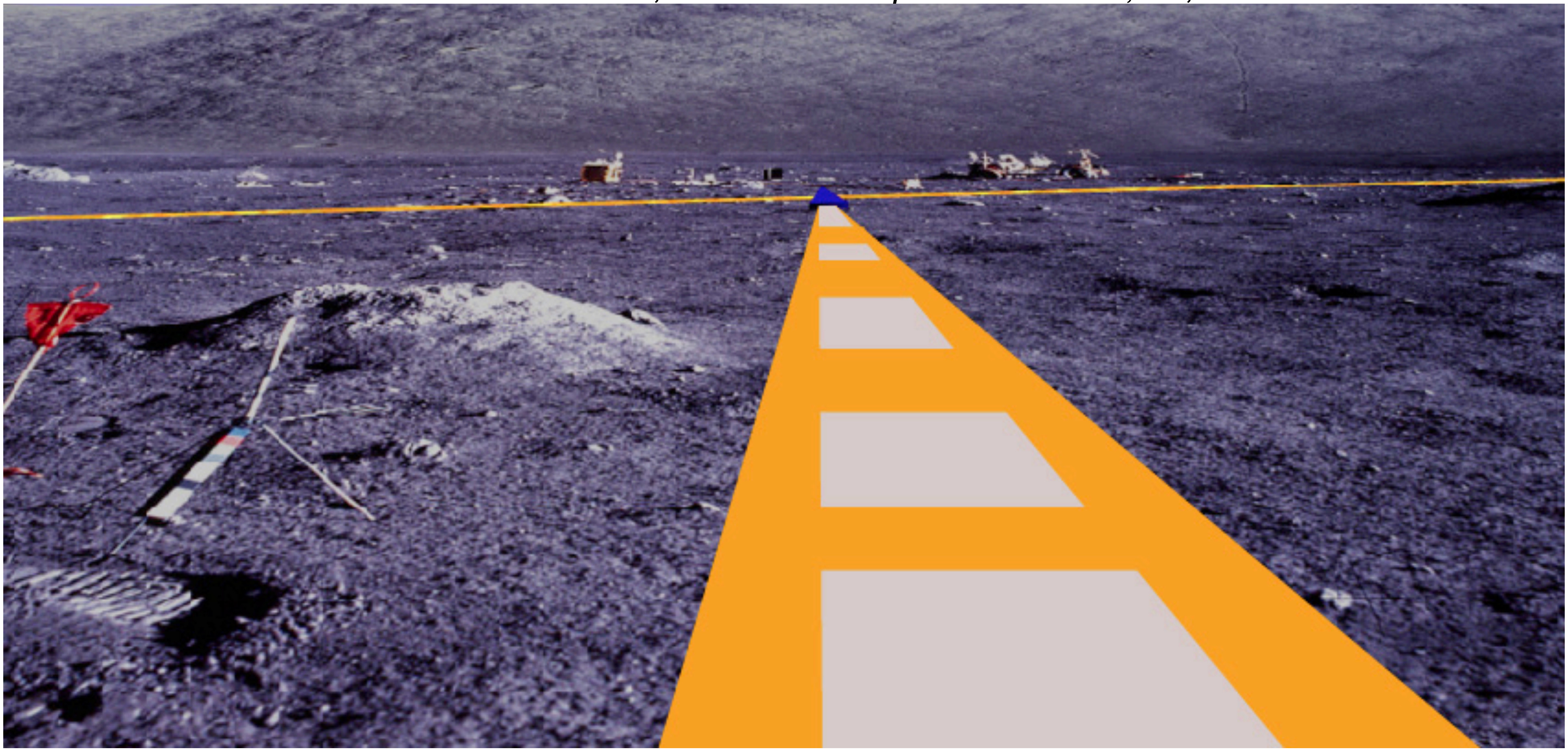
South Pole-Aitken Basin (SPAB): A spacecraft is in view of (200°E, 60°S) for 5 – 7 days at a time, with a 5° elevation mask.



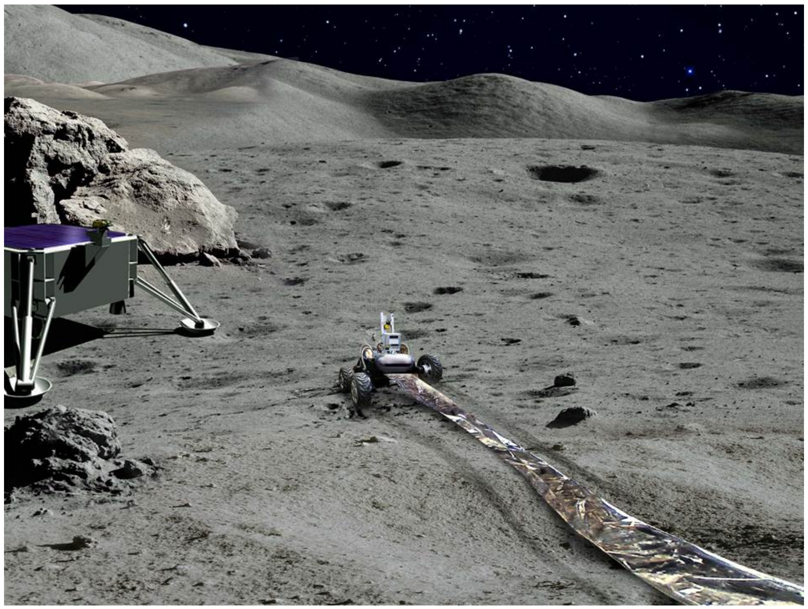
Low Frequency Kapton Array on Lunar Farside



- Lunar farside is free of human radio frequency interference and absorption/refraction effects produced by Earth's ionosphere at frequencies <100 MHz.
- Kapton film is a robust, light-weight backbone for an array of low frequency antennas that can be deployed by a modest rover. Kapton "arms" will be 1-m x 100-m x 0.025 mm.
- See Lazio et al. 2011, *Advances in Space Research,* 48, 1942.



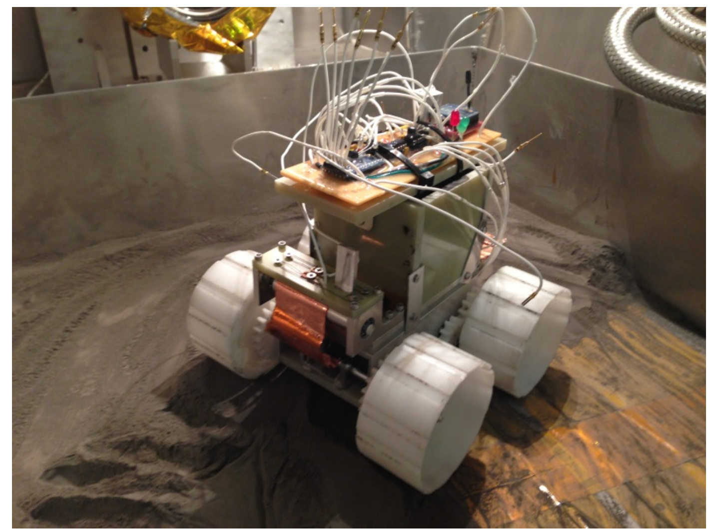
Deployment of Kapton Film Antennas



Artist's conception of roll-out Kapton film antenna on Moon's farside (South Pole Aitken Basin)

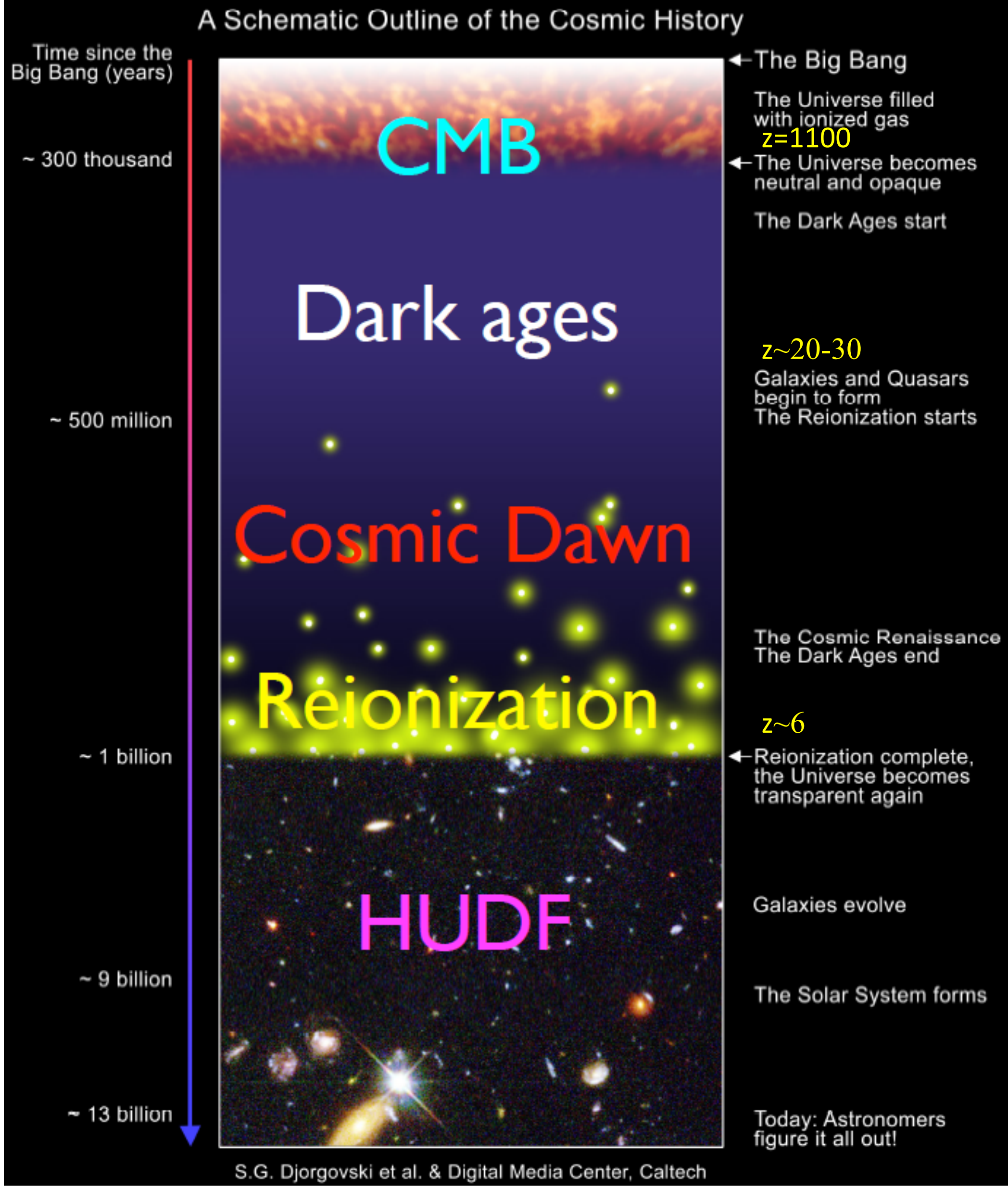
Kapton antenna test in New Mexico

- Metallic conductor deposited on surface of Kapton film.
- Unrolled, deployed by rover remotely operated from Orion on radio-quiet farside.
- Operate at ν < 100 MHz.
- Film tested in vacuum chamber, with thermal cycling & UV exposure similar to lunar surface conditions, & in the field.



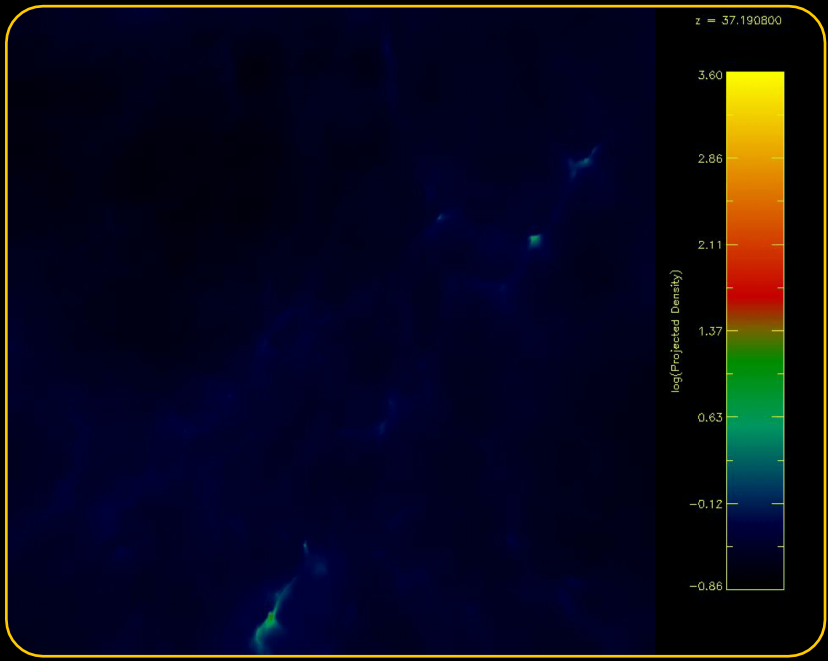
Rolling out Kapton film inside vacuum chamber with teleoperated mini-rover

The First 0.5 Billion Years of the Universe



The First Stars

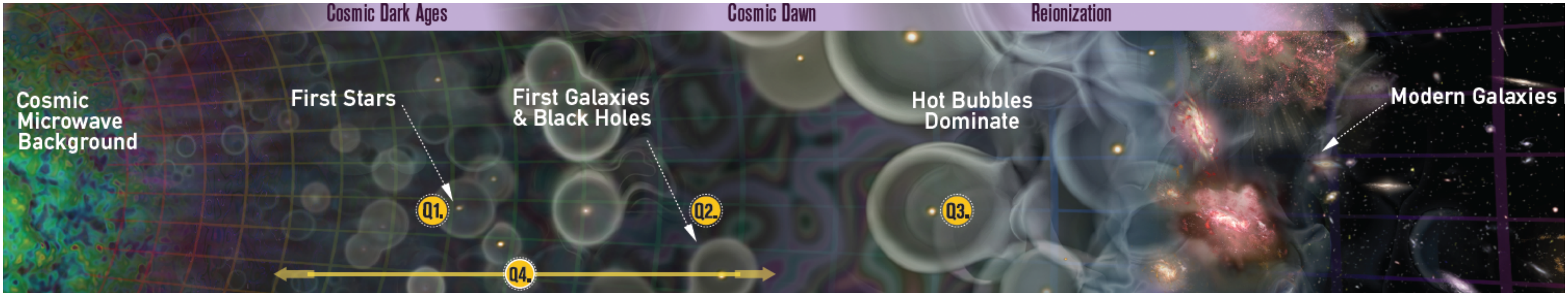
Simulation by John Wise, Georgia Tech



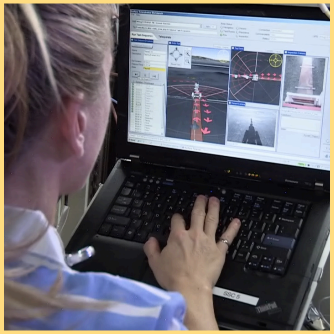
Astrophysics Decadal Survey & Astrophysics Roadmap identifies Cosmic Dawn as a top Science Objective

- "A great mystery now confronts us: **When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our cosmic dawn?** *New Worlds, New Horizons* (Astrophysics Decadal Survey).
- "How Does our Universe Work? - **Detailed map of structure formation in the Dark Ages via 21-cm observations**… Capabilities required: ***Cosmic Dawn Mapper* (21-cm lunar surface radio telescope array).**" *NASA Astrophysics Division Roadmap* (2013 draft).

"What were the first objects to light up the Universe and when did they do?"



"Fastnet" Mission Simulation with ISS

Planning	Phase 1	Phase 2	Phase 3
Pre-Mission Planning	**Surveying**	**Telescope Deployment**	**Telescope Inspection**
			
Ground teams plan out telescope deployment and initial rover traverses.	Crew gathers information needed to finalize the telescope deployment plan.	Crew monitors the rover as it deploys each arm of the telescope array.	Crew inspects and documents the deployed telescope for possible damage.
	Crew Session 1	Crew Session 2	Crew Session 3
Spring 2013	***June 17, 2013***	***July 26, 2013***	***August 20, 2013***

Phase 1 Summary

Objectives

1. Demonstrate that crew can remotely operate surface robots from inside a flight vehicle to perform exploration work
2. Mature technology required for crew control of surface telerobots (specifically robotic control interfaces for crew)
3. Identify requirements and gaps for research and technology development programs

Success Criteria

1. Demonstrate crew performing surface **survey, payload deployment,** and **inspection** using a planetary rover
2. Complete the TRL advancements listed from Authority to Proceed (ATP) to Phase 1 end
3. Complete a critical incident analysis of the demonstration

Test approach

Focus

- Study crew-centric telerobotics under flight conditions
- Identify technology gaps, risks, and issues

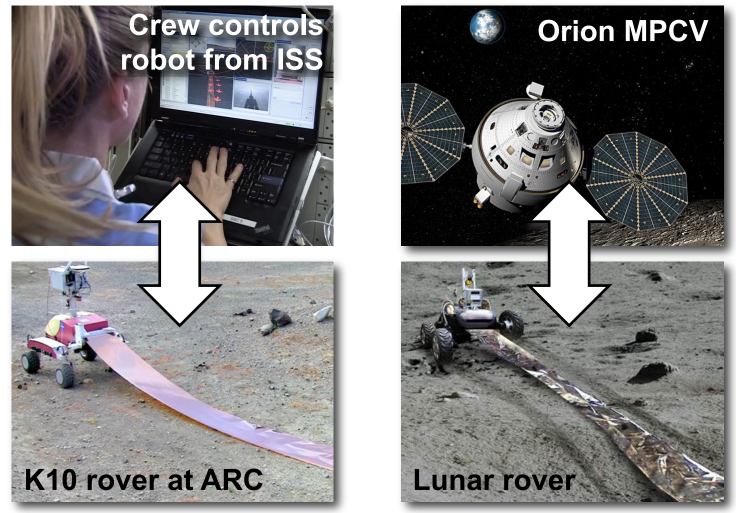
Data Collection

- Data communication: data transfers, delay, message rate
- Robot telemetry: position, power, health, instrument use
- User interface: mode changes, data input, button clicks
- Operations: sequence generation, task success/failure
- Crew questionnaires: workload, situation awareness

Metrics

- Crew: Work Efficiency Index, Situation Awareness Global Assessment Technique, NASA Task Load IndeX (TLX)
- Robot: Mean time bet. intervention, Mean time to intervene
- System: Time on Task, Idle Time, Uplink/Downlink data

Surface Telerobotics Phase 1



Human Exploration Concept

TRL Advancement	ATP *Jan 2012*	Phase 1 end *Aug 2013*
User Interface		
Crew interface for robot control	5	6
In-line metrics, summarization, and notification systems	4	7
Robot data monitoring & verification	5	7
Robot on-board autonomy supporting interactive commanding mode	4	6
Communications		
Robot command and telemetry messaging (DDS on IP)	5	7
Short time-delay mitigation	4	6

“Firsts” from ISS Surface Telerobotics Tests

- First simulation of a human-robot "Waypoint" mission concept (Orion above Lunar Farside).
- First real-time teleoperation of a planetary rover from the ISS.
- First astronaut to interactively control a high-fidelity planetary rover in an outdoor analog testbed.
- Provide opportunities for student training on a realistic Waypoint mission simulation.

University of Colorado students Laura Kruger, Miles Crist, and Michael Leitshuh during ISS Crew Session 2 on 26 July 2013 at NASA Ames.

Phase 2 Overview

Objectives

- Reduce risk for **human-robot orbital** exploration missions (Moon + Mars)
- Focus on **enhancing ops knowledge**
- Demo **crew-controlled telerobotics** using ISS as an exploration testbed

Rapid project (18 months)

- **Build on Phase 1**: same robot + crew UI + ground testbed + data comm infrastructure
- FY14 – preparation / **ground test**
- FY15 – **ISS demo** (Expedition 44)
- Report on operational / technical gaps, lessons learned, and recommendations

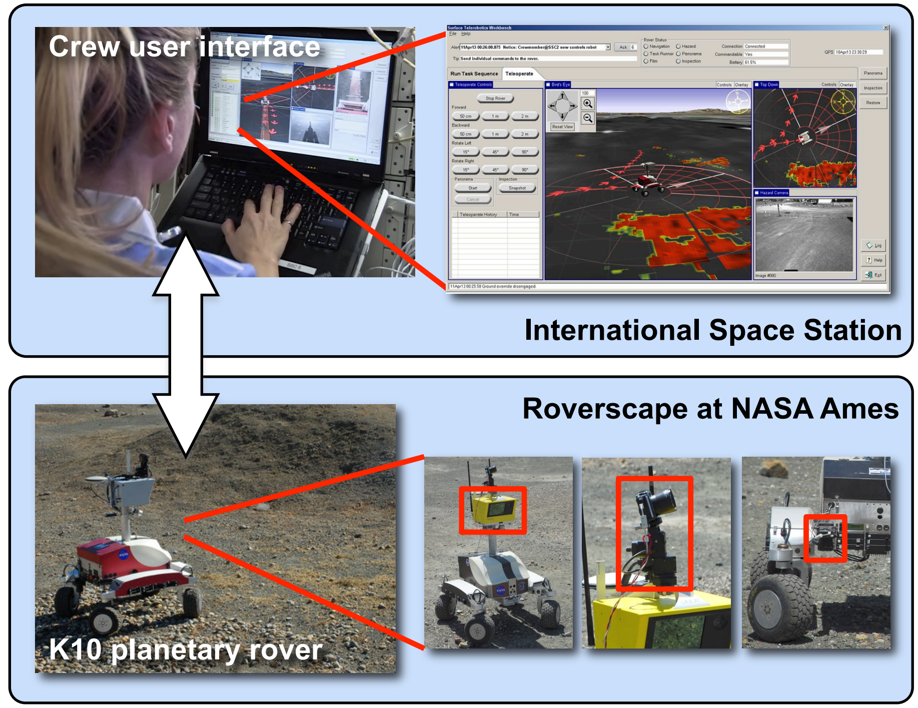
Test options

A. Realistic **datacomm**

B. **Orion** constraints

C. Different **surface tasks**

D. **Multi-robot** conops
(crew-control and crew/ground-control)



Collaborations

- Lockheed Martin Corp. / Denver
- Advanced Exploration Systems (HEOMD)
- NASA Solar System Exploration Research Virtual Institute (HEOMD / SMD)
- ESA METERON project
  (interagency agreement in process with State Dept)

Example Phase 2: Orion Constraints

Objectives

1. Study **integration impacts** to Orion
2. Assess viability of **off-loading rover processing** to Orion
   - Processor and storage requirements
   - Comm requirements
3. Test **crew autonomy** (real-time decision making)

Approach

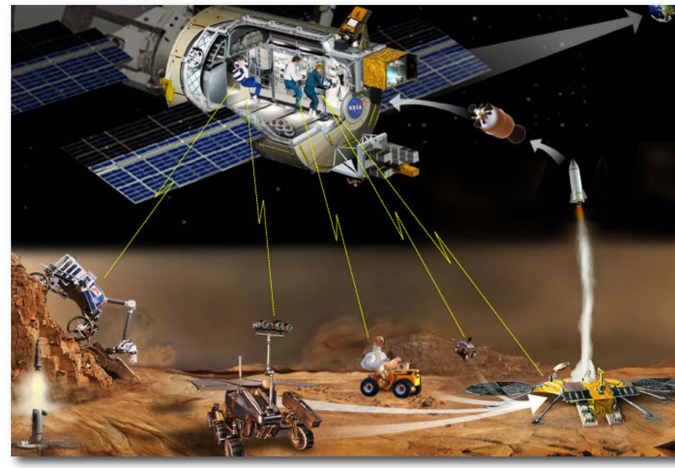
1. Repeat **Phase 1 mission sim with moderate mods**
   - More detailed crew training on robot operations
   - Crew operates with little support from mission control
   - Human-in-the-loop contingency handling: terrain hazards, rover subsystem failures, etc.
2. Provide crew with more system level control of rover
3. Off-board some rover functions (hazard detection, localization, etc) to simulated Orion computer

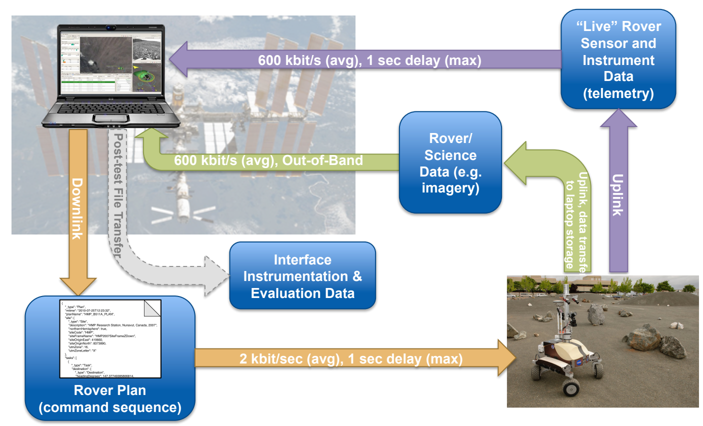
Metrics

1. Crew: Work Efficiency Index, Situation Awareness Global Assessment Technique, Bedford Workload Scale
2. Robot: Mean time between/to intervention (MTBI, MTTI)
3. Task: Time on Task, Idle Time, Success rate
4. Spacecraft: CPU load, RAM/disk used, bandwidth used

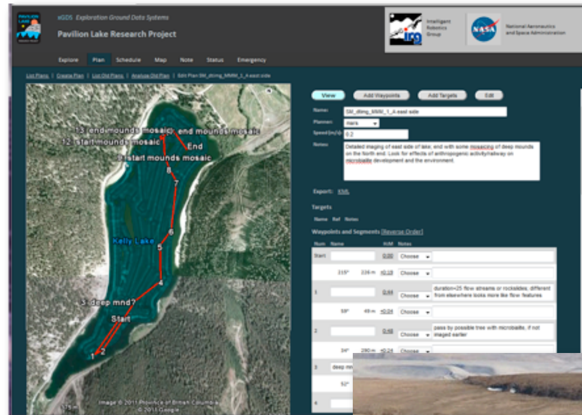
Collaboration

1. Lockheed: Orion computing options, Orion integration requirements, participation in ground testing **(in-kind support)**





Example Phase 2: Different Surface Tasks



Objectives

1. Examine **other surface tasks** that are more unstructured, complex and unpredictable
2. Assess **system capability** to support increased SA and rapid switching between robot control modes.
3. Enhance **operational knowledge** of crew-controlled surface telerobotics

Approach

1. Run **new mission sim** incorporating one (or more) of:
   - Assembly and cabling of a functional radio telescope
   - Planetary fieldwork (very different than on-orbit servicing)
2. Enhance crew user interface to support new tasks
   - Integrate xGDS ops software (AES)
   - Integrate manipulator and/or mechanism control
3. Modify robot to support new tasks

Metrics

1. Crew: Work Efficiency Index, Situation Awareness Global Assessment Technique, Bedford Workload Scale
2. Robot: Mean time between/to intervention (MTBI, MTTI)
3. Task: Time on Task, Idle Time, Success rate

Collaboration

1. Lockheed: robot arm/ mechanism, Orion integration studies, participation in ground testing **(in-kind support)**
2. AES ASO project: adapt xGDS software for crew use
3. SSERVI: education and public outreach (live-streaming and student interaction)

Example Phase 2: Multi-Robot Conops

Objectives

1. Examine how **multiple humans and robots** can be employed for orbital missions
2. Test **different control strategies** for two robots
   - Single crew operates both robots
   - Crew + mission control independently operate robots
3. Enhance **operational knowledge** of crew-controlled surface telerobotics

Approach

1. Repeat **Phase 1 mission sim with major mods**
   - Two robots (ARC & JPL) operating in parallel
   - Diifferent modes of control
2. Enhance crew user interface
   - Support multiple robots
   - Integrate data sharing (crew/mission control)
3. Run tests to study operational efficiency and bottlenecks

Metrics

1. Crew: Work Efficiency Index, Situation Awareness Global Assessment Technique, Bedford Workload Scale
2. Robot: Mean time between/to intervention (MTBI, MTTI)
3. Task: Time on Task, Idle Time, Success rate

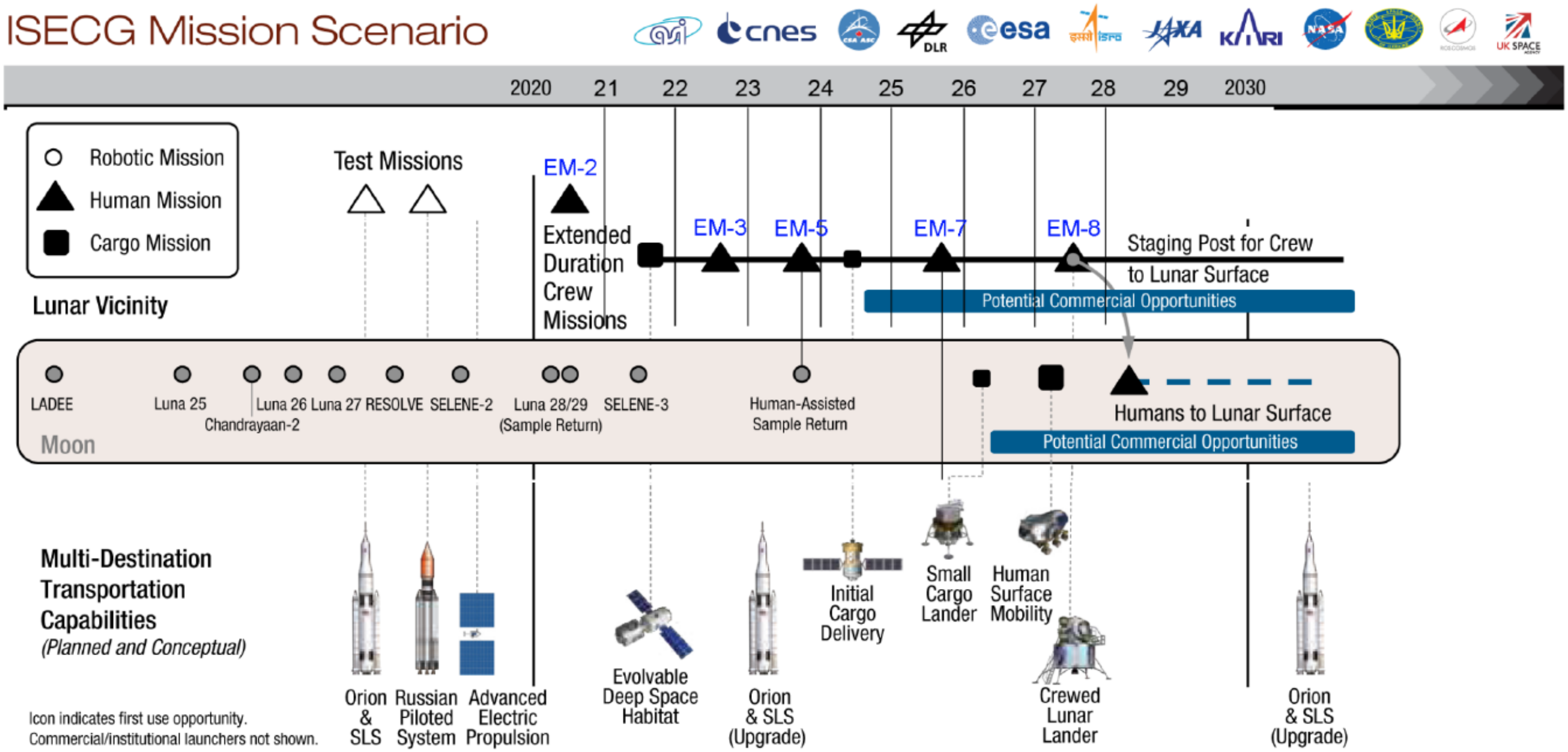
Collaboration

1. Lockheed: Orion integration studies, participation in testing, ground robot control **(in-kind support)**
2. SSERVI: education and public outreach (ground robot control with students/public)

Global Exploration Roadmap: Multiple opportunities to test Surface Telerobotics

Developing the Human Exploration Elements

- NASA's SLS and Orion vehicles
- ESA service module



Detail of illustration from the GER (2013) with small modifications (courtesy D. Kring)